Speech-based Interaction with In-vehicle Computers: The Effect of Speech-based E-mail on Drivers' Attention to the Roadway

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As computer applications for cars emerge, speech-based interfaces provide an obvious alternative to the visually demanding graphical user interfaces common on desktop applications. However, speech-based interfaces may pose cognitive demands that could undermine driving safety. This study uses a car-following task to evaluate how a speech-based e-mail system affects drivers' response to a periodically braking lead vehicle. A baseline condition with no e-mail system was compared to a simple and a complex e-mail system in both simple and complex driving environments. The results show a 30% (310 msec) increase in reaction time when the speech-based system is present. Subjective workload ratings also indicate that speech-based interaction introduces a significant cognitive load, which is highest for the complex e-mail system. A simple model of driver performance shows that, in imminent collision situations, the 310 msec delay induced by the speech-based interface can have important safety implications.

Keywords: Automatic speech recognition, speech-based interface, driver distraction, attention, driver performance model

INTRODUCTION

The evolution of computers has made a variety of in-vehicle information systems possible (Lee, 1997; Lee, Kantowitz, Hulse, & Dingus, 1994). With the development of laptop, palmtop, and wearable computers, together with cellular communication technology, the idea of placing computers in cars and trucks has become very attractive. These new information systems can enhance mobility and productivity, but they may also distract drivers and undermine safety. The recent introduction of the AutoPC and a variety of in-vehicle navigation systems illustrate this important trend. Automatic speech-recognition (ASR) and text-to-speech technology offer an option for a driver-vehicle interface that may not distract drivers as standard controls and displays might. Recent developments in ASR and text-to-speech technology may make it possible to talk and listen to an in-vehicle computer (Leiser, 1993). Speech-based interaction offers a promising alternative to the graphical user interface of desktop computers, one that *seems* consistent with the visual and motor demands of driving—a speech-based interface allows drivers to keep their hands on the wheel and eyes on the road. However, little research has addressed the cognitive load of a speech-based interface for in-vehicle computers and none has examined its effect on driving performance.

Attention to the road and speech-based interactions

Many researchers and designers have recognized the potential of visual displays to distract drivers (Lunenfeld, 1989; Mollenhauer, Hulse, Dingus, Jahns, & Carney, 1997; Srinivasan & Jovanis, 1997), but few have addressed the potential for auditory displays and verbal controls to produce a similar effect. Although speech-based interfaces have not been examined directly, substantial research has examined the effect of cellular and mobile telephones on driving performance and safety. Comprehensive reviews of voice communications and driving suggest that voice inputs and auditory displays will be an important component in future vehicles, and that speech-based interaction has the potential to distract drivers and degrade safety (Goodman, Tijerina, Bents, & Wierwille, 1999; McKnight & McKnight, 1993; Parkes, 1993). Evidence that cellular telephones can distract drivers comes from epidemiological data of accidents and controlled simulator and on-road studies of driving performance. For example, a statistical analysis of accident data showed that drivers with cellular telephones are four times as likely to be involved in a crash and that hands-free telephones provide no safety benefit (Redelmeier & Tibshirani, 1997; Violanti, 1997). A large number of on-road and simulator studies have shown substantial increases in driver response times during telephone conversations (Alm & Nilsson, 1995; Brown, Tickner, & Simmonds, 1969). A recent study directly compared the visual demands of entering numbers into a keypad to the cognitive demands of a memory and addition task. The results showed that both tasks impaired drivers' ability to detect braking vehicles by 500 msec (Lamble, Kauranen, Laakso, & Summala, 1999). Speech-based interaction with in-vehicle computers shares many of the characteristics of a cellular telephone conversation, and a poorly designed interface may distract drivers and increase reaction time.

Findings from basic research on attention also confirm the potential for speech-based interaction to distract drivers. The multiple resource theory of attention suggests that speech-based interaction with an in-vehicle computer would be less detrimental to the manual control task of driving than a visual display (Wickens, 1984; Wickens & Hollands, 1999). Speech-based interaction should demand the resources associated with auditory perception, verbal working memory, and vocal response. Driving should demand the resources associated with visual perception, spatial working memory, and manual response. Because these resources are independent timesharing should be quite efficient. However, the attentional demands that speech-based interaction may place on common central processing resources might undermine timesharing and compromise driving safety. Others researchers suggest that central processing limits will predominate, and that a single channel, limited-capacity theory better reflects how speech-based interaction might undermine driving safety (Moray, 1999). More important than the specific attentional resources may be the strategies of task management (Chou, Madhavan, & Funk, 1996; Funk, 1991; Raby & Wickens, 1994; Tulga & Sheridan, 1980). Initial data suggests that drivers may not prioritize and manage their speech-based tasks effectively. Specifically, studies have shown that a concurrent verbal task increased drivers' propensity to take risks (Horswill & McKenna, 1999), and that drivers did not compensate as verbal interactions slowed their reaction times (Alm & Nilsson, 1995). These results suggest that drivers may not fully recognize the distractions of speech-based interaction and may fail to compensate for the distraction that these demands induce.

The distraction and safety consequences of speech-based interfaces are not easily extrapolated from research on speech communication with a cellular telephone or standard concurrent verbal tasks. Talking to a computer is fundamentally different than talking on a cellular telephone or to a passenger. Some simple differences include the added cognitive load of interpreting a poor quality synthetic voice (Smither, 1993). Recalling commands and remembering system syntax could also add a substantial demand not experienced in conversations. Similarly, the spatial demands of navigating a complex menu structure may introduce a cognitive load that may compete with the spatial demands of driving in a way that a conversation would not (Vicente & Williges, 1988). In addition, unlike conversation with passengers, current in-vehicle computers are not able to modulate their interaction with the driver as a function of the driving situation. On the other hand, interaction with a speech-based system may be less distracting than conversations because drivers may have more flexibility to abort an interaction with an in-vehicle computer. The safety concerns of cellular telephone conversations and the unique characteristics of a speech-based interface make an empirical investigation of speech-based interfaces critical.

The effect of the speech-based interface may interact with the complexity of the driving task. As the driving environment becomes more complex, more attentional resources are needed to maintain performance. Harms (1986) used a secondary reaction time task to show that driving in a complex environment (a village) demanded more attention than driving in a simple environment (a highway). Higher traffic density, traffic signs, and more elaborate road arrangements characterized the complex driving environment of the village. Importantly, attentional demand, as measured by mean reaction time, was strongly related to the density of accidents along the routes.

Previous research with cellular telephones suggests that speech-based interaction with an in-vehicle computer is likely to increase the cognitive load on the driver and draw attention away from the roadway. This could undermine driver awareness of the roadway and delay driver response to roadway events. Increasing the complexity of the in-vehicle computer system could exacerbate these effects. Increasing the complexity of the driving environment might also increase the drivers' cognitive load, and the interaction between the two could further delay drivers' response to roadway events. This experiment investigates these hypotheses with the general aim of identifying ways to minimize potential safety problems of speech-based interfaces.

METHOD

This study used a medium-fidelity simulator to evaluate the distraction potential of a speech-based interface for a prototypical in-vehicle computer application, an e-mail system. Twenty-four younger drivers drove a series of five 5-7 minute scenarios, in which they interacted with the e-mail system and responded to the erratic braking of a lead vehicle. Measures of reaction time to the braking of the lead vehicle, of the subjective mental workload, and of drivers' situation awareness were collected.

Apparatus

A fixed-based, medium-fidelity driving simulator was used to conduct the experiment. The driving simulator used a 1992 Mercury Sable configured with the Hyperion Technologies Vection Research Simulator (VRS). The VRS is a fully integrated, high-performance driving simulation system designed for use in ground vehicle research and training applications. The VRS uses a real vehicle cab (Mercury Sable) that has been modified to include a 50 degree visual field of view, full instrumentation with actual gauges, force feedback operator controls, and a rich audio environment. The fully textured graphics are generated by state-of-the-art PC hardware that delivers a 60 Hz frame rate at 1024 x 768 resolution.

Driving scenarios for the VRS are generated through a graphical software package called HyperDrive. HyperDrive uses a tile-based scene authoring system in which segments of roadway can be connected like pieces of a puzzle to create a fully populated driving environment. In addition, vehicles may be added to the scene and given interactive behaviors through a combination of graphical tools and a scripting language. All simulation models for roadway layouts, markings, and signage conform to American Association of State Highway and Transportation Officials (AASHTO) and Manual of Uniform Traffic Control Devices (MUTCD) design standards.

An voice-activated e-mail system was used to test the effects of voice interaction with an in-vehicle computer on drivers' attention to the roadway. The e-mail system was developed using Microsoft Visual Basic and Microsoft Text-to-Speech software. The ASR function was fulfilled by an experimenter, which gave the system perfect speech recognition performance. There were two e-mail systems used in this experiment: simple and complex. Both e-mail systems allowed the driver to perform e-mail functions with voice commands. The simple system consisted of three levels of menus with two options for each menu. The complex system consisted of four to seven options for each menu.

Participants

The participants included 24 drivers who had normal or corrected to normal vision. All had a valid driver's license, were undergraduate students of the University of Iowa, and ranged in age from 18 to 24. They were paid $6.50 an hour for the time they took to complete the experiment.

Experimental design

The experiment used a $2X2^2$ factorial between/within subject design. Complexity of the e-mail system was a between-subject variable, complexity of the driving environment, and availability of the system were within-subject variables. The number of menus and the number of options for each menu defined the complexity of the e-mail system. Traffic density, intersection density, and the scenery (houses, barns, fences, and animals) defined the complexity of the driving environment. Whether or not the driver was able to use the e-mail system defined the availability of the system. When the system was not available the driver did not interact with the in-vehicle system and focused on driving the car.

Each participant drove in one practice scenario and four experimental scenarios. The practice scenario familiarized the participant with the driving simulator and the voice activated e-mail system. The practice and experimental scenarios were approximately 5 minutes in length. During each scenario, the driver followed a lead vehicle with a headway of 1.8 seconds and a speed of approximately 40 mph (64.4 kph) that braked periodically with a deceleration of 6.9 ft/s^2 (2.1 m/s^2). The lead vehicle braked at a random point four times during each scenario. The driver was instructed to maintain a speed between 40 and 45 mph (64.4 and 72.4 kph) and the speed of the lead vehicle was automatically adjusted to maintain a 1.8-second headway. Two of the four scenarios involved the simple driving environment (one with voice interaction and one without). The other two scenarios involved the complex driving environment (again, one with voice interaction and one without). A Latin Square design was used to counterbalance the order of scenarios.

The dependent measures included driving performance, situation awareness, subjective workload, and perceived distraction. This paper reports the results for driving performance, subjective workload, and perceived distraction. Driving performance was characterized by the drivers' reaction time to the deceleration of a lead vehicle. The reaction time was measured from the onset of the lead vehicle deceleration to the point at which the driver began to release the accelerator (Summala, Lamble, & Laakso, 1998). After each scenario, drivers rated their subjective workload on the six NASA Task Load Index (TLX) scales (Hart & Staveland, 1988). The scales range from 0 to 100 and were divided into 20 increments. For those scenarios where the e-mail system was available, the drivers also rated their perceived distraction on a scale modeled after the NASA TLX.

Procedure

After the participants were introduced to the experiment and signed the informed consent forms, they were randomly assigned to either the complex or the simple e-mail system. They were then given a description of how to operate the voice-activated e-mail system and of the task they were to perform. The first scenario was a practice scenario. Participants in each group were given a generic task that corresponded to their assigned system (simple e-mail system or complex e-mail system). When they had completed the practice scenario, participants began the experimental scenarios. Before each one, participants were informed whether or not they would be using the speech-based e-mail system. If drivers were to use the e-mail system, they were given a description of the task. For example, in one scenario drivers were asked to: "*Read a new message from your boss concerning the project budget. Also, read messages containing vendor estimates for the project. Correctly reply to your boss. The task is completed when you have gone through all messages and you have exited the system.*" The drivers were then informed that the speed limit was 45 mph and the minimum speed was 40 mph. They were also told to follow the lead vehicle at all times and to drive as they would normally drive. During each scenario in which the e-mail system was available, the experimenter told them when to begin the e-mail task. After each scenario, participants were given questionnaires that included the situation awareness probe questions, the NASA TLX scale, and the rating scale for perceived distraction.

RESULTS

The data were analyzed using the general linear model (GLM) procedure provided by SAS. The model parameters were drive complexity, e-mail system complexity, availability of the e-mail system, subject number, and their interactions. Additionally, for reaction time, the braking occurrence (first through fourth) was also included. For significant main effects, $\hat{d}$, a standard measure of effect size, is reported. The measure $\hat{d}$ is defined as the difference between the means divided by their pooled standard deviation.

Reaction time to lead vehicle deceleration

Drivers' reaction time was measured from the onset of the lead vehicle deceleration to the point at which the driver began to release the accelerator. A logarithmic transform was applied to normalize the data. The statistical results are reported for the transformed data, but the means are reported for the raw data. Drivers responded more slowly when the e-mail system was available, with a mean reaction time of 1.32 seconds compared to 1.01 seconds, $F(1,22)=10.92$, $p<0.01$, $\hat{d}=0.40$. The complexity of the driving environment also increased reaction time from 1.00 to 1.32 seconds, $F(1,22)=7.26$, $p<0.05$, $\hat{d}=0.34$. Interestingly, the effect size for roadway complexity and availability of the e-mail system are approximately equal. Contrary to the hypothesis, system complexity did not have a statistically significant effect on reaction time—the mean reaction time for the complex e-mail system was 1.41 seconds, compared to a mean reaction time for the simple system of 1.23 seconds, $F(1,22)=0.18$, $p=0.68$. Figure 1 shows the joint effect of system availability and complexity of the driving environment. The error bars represent ± one standard error. These two factors are additive and do not interact, $F(1,21)=0.29$, $p=0.59$.

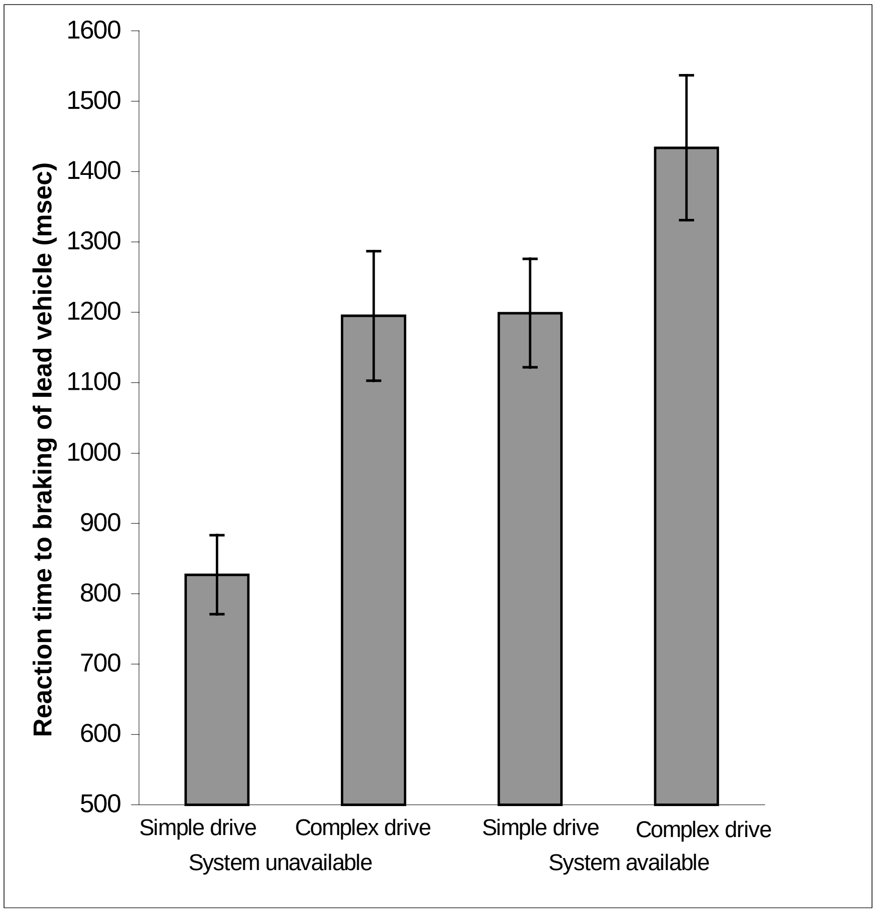

Figure 1. The effect of the availability of the e-mail system and the complexity of the driving environment on reaction time to an intermittently braking lead vehicle.

Subjective workload and perceived distraction

The NASA TLX data were analyzed by combining the six scales, with each scale receiving an equal weight. The availability of the e-mail system had a large effect on the combined NASA TLX measure, with a rating of 47.0 when the system was available and 27.1 when it was not, $F(1,22)=162.97$ $p<0.001$, $\hat{d}=1.34$. This main effect was dependent upon an interaction with system complexity, $F(1,22)=21.09$, $p<0.001$. Not surprisingly, when the e-mail system was not available the subjective workload was almost equal—27.8 for the simple system and 26.4 for the complex system. When the system was available, the subjective workload was greater for the complex system, 53.3, compared to 40.7 for the simple system, $F(1,22)=4.58$, $p<0.05$, $\hat{d}=0.822$. Interestingly, the complexity of the driving environment did not have a statistically significant effect on the subjective workload, $F(1,22)=0.01$, $p=0.93$. The drivers' ratings of perceived distraction due to the e-mail system indicated that the complex system was perceived as more distracting than the simple system, $F(1,22)=6.99$, $p<0.05$, $\hat{d}=1.02$, with a mean rating of 37.7 for the simple system and 59.0 for the complex system. Interestingly, the effect size of e-mail complexity for perceived distraction was much greater than the effect of system availability on reaction time ($\hat{d}=0.40$). Figure 2 shows the effect of the availability and complexity of the e-mail system on subjective workload and perceived distraction.

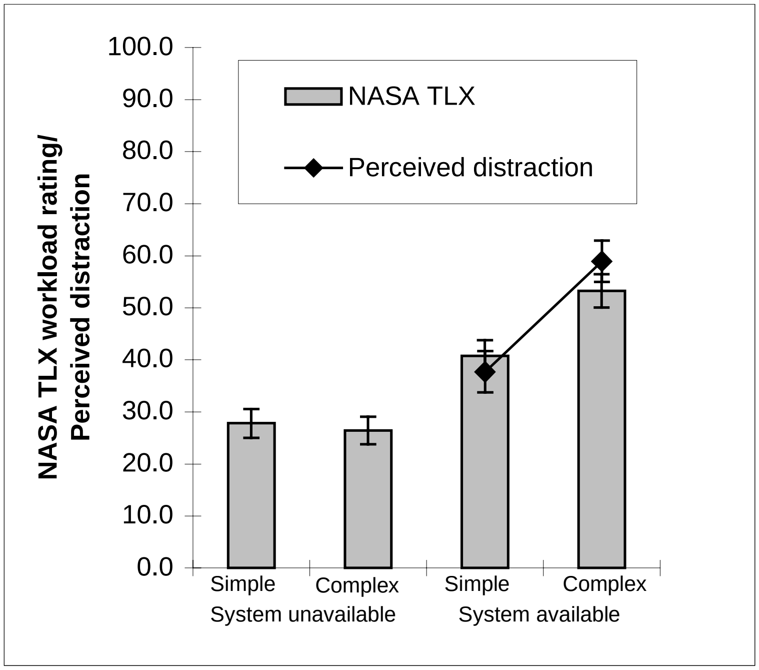

Figure 2. The effect of the availability and complexity of the speech-based e-mail system on subjective workload and perceived distraction.

DISCUSSION AND CONCLUSIONS

This study examined how drivers react to speech-based interfaces for in-vehicle information systems. Specifically, it examined the degree to which e-mail tasks, performed with an automatic speech recognition and text-to-speech interface, distract drivers and degrade driving safety. Safe use of in-vehicle information systems depends on whether interactions interfere with driving, whether drivers recognize the interference, and whether drivers can modulate their attention to the in-vehicle system to minimize the consequence of this interference. The results of this experiment begin to address these issues and provide an initial assessment of the impact of a speech-based interface for an in-vehicle computer on driving safety.

Degree of distraction and safety

The results show that a speech-based interface is not a panacea that eliminates the distraction potential of in-vehicle information systems. A speech-based interface can distract drivers. The data show a 30% increase in reaction time and a large increase in subjective workload due to the cognitive demands of speech-based interaction. Although system complexity did not increase drivers' reaction time, it did increase the subjective workload and perceived distraction. These results show that speech-based interaction draws upon the cognitive resources required for driving, leading to a 310 msec increase in the time it takes for drivers to react to an intermittently braking lead vehicle. This increase is comparable to the effect of cellular phone interactions; in a study with a similar car following task, reaction time increased by 385 msec for an expected event (Alm & Nilsson, 1994), and by 560 msec for an unexpected event. Because the drivers in this experiment responded a total of 20 times to the periodic braking of the lead vehicle, response to an unexpected event would likely be even further delayed. Because the delay in reaction time due to the speech-based interface and the roadway complexity is additive, the effect of speech-based interaction in complex driving environments could be particularly dangerous. These results show that a speech-based e-mail system can constitute a distraction similar to that of simple verbal reasoning tasks performed with a hands-free cellular telephone.

A simple deterministic simulation of driver performance in an imminent collision situation provides some additional insight into the safety consequences of the 300-msec delay (Brown, Lee, & McGehee, In review). A simple model of the driver and the environment was used to evaluate the effect of a 300-ms delay on drivers' ability to avoid rear-end collisions. The model consisted of four components. The first two components modeled the dynamics of the lead and following vehicles. The third component modeled the detection of an imminent collision situation and the activation of the driver's response. In this component, the driver response was modeled based on the assumption that response to a braking lead vehicle would be initiated when Time-to-Collision (TTC) dropped below a specified threshold. TTC was augmented with a speed correction to better approximate driver performance (Hirst & Graham, 1997). The fourth component modeled drivers' braking response. The braking response was modeled as a reaction time delay followed by a step response input to the brake. The step brake response is indicative of emergency braking in which a constant brake pressure is applied to stop the vehicle.

To assess the effect of a 300-msec delay, we considered a case in which drivers responded 300 msec later than they would have without the email system. To model driver response, a TTC threshold of 3.0 seconds was used and a 1 ft/mph speed correction was applied, generating an earlier response at higher speeds. We examined a range of conditions by varying lead vehicle deceleration and headway. Deceleration of the lead vehicle was varied from 0.40 g to 0.85 g at 0.05-g increments. The initial headway was also varied from 1.00 second to 3.00 seconds in 0.25-second increments. The deceleration of the following vehicle was 0.75 g, and the driver reaction time was set at 1.5 seconds and 1.8 seconds. The 1.8 second reaction time reflects the 300 msec delay induced by the speech-based interaction. For each of these reaction times, the model output was examined to determine whether the vehicles collided, and if they did, at what velocity. Table 2 shows how a 300 msec delay increases the number of collisions and the collision velocity for the speeds of 35 and 55 mph. The 1.8-second response time resulted in a 3.5% to 38.5% increase in collisions and a 27.3% to 80.7% increase in collision velocity. This analysis shows that a 300-msec meaningfully affect driving safety.

Table 2. The effect of a 300 msec delay at 35 mph and 55 mph for lead vehicle decelerations from 0.40 g to 0.85 g and for headways from 1.0 to 3.0 seconds.

Initial Speed	Percent increase in collisions	Percent increase in collision velocity
35 mph	38.5%	80.7%
55 mph	3.5%	27.3%

Implications for design

These results of this experiment support two important conclusions. First, speech-based interaction with in-vehicle information systems places a cognitive load on drivers that can affect driving performances. Speech-based interaction draws upon some of the same cognitive resources as driving and so can distract drivers just as visual displays and manual controls can. In driving conditions that require an immediate response, this distraction can undermine driving safety. Second, in this experiment, drivers generally recognized that speech-based interaction imposes a cognitive load and that increasing the complexity of the interaction imposes a greater load and is perceived as more distracting. An accurate perception of the distraction caused by an in-vehicle computer is a minimum requirement for modulating attention to the roadway. If the degree of distraction is underestimated then drivers may fail to shed the in-vehicle tasks when the driving tasks require full attention. Future research should examine how well this perceived distraction corresponds to the actual level of distraction. These results suggest speech-based interfaces should not be used indiscriminately and that careful attention to their design and the complexity of the underlying system is critical.

These conclusions depend on how well driver behavior in a simulator generalizes to actual on-road driving. Several caveats must temper this generalization. Because this study was conducted in a simulator, drivers were not exposed to the same risk as on an actual roadway. Awareness of the lack of any severe consequence may affect how drivers modulate their attention, and lead them to devote more attention to the in-vehicle system. In addition, this study exposed drivers to the speech-based system for only one hour and did not consider long-term adaptation. Experience may have decreased the cognitive demand as drivers learned to use the system, better understood the degree of distraction, and learned to modulate their attention to the system. Even with these caveats, this study has broad implications because speech-based interaction is an appealing interface solution for in-vehicle information systems in that it does not *seem* to interfere with driving. In addition, several factors may make the effects observed in the simulator more important in actual driving situations. Because this experiment used a person to fill the role of the ASR system, the ASR errors were minimized. ASR errors are likely to occur in an actual driving environment and they are also likely to increase drivers' cognitive load and undermine attention to the road. Likewise, this experiment operationalized system complexity in one way. It is likely that other factors affecting complexity that were not manipulated in this experiment could also increase the cognitive load of speech-based interactions. This study shows that a speech-based interface can draw upon the some of the same cognitive resources used for driving. If drivers fail to modulate their attention appropriately to accommodate these demands, then speech-based interaction can undermine driving safety.

ACKNOWLEDGEMENTS

This research was funded in part by grant #R49-CCR703640-10 of the National Center for Injury Prevention and Control.

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